High-sensitivity direct detection optical communication system that operates in sunlight

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ABSTRACT

In freespace laser communication systems, optical background noise rejection is a very important issue. We have designed and built a building to building direct detection optical communication system that uses a Faraday Anomalous Dispersion Optical Filter (FADOF) in the receiver. The FADOF is an narrow bandpass optical filter, which can provide a background noise rejection of $10^5 \sim 10^6$, while transmitting the signal with up to 80% efficiency. The FADOF also has a signal bandwidth that is variable between 0.5 GHz and 5 GHz, a field-of view that is flat over $\pm 20^\circ$. FADOFs offer new capabilities to freespace laser communication by effectively reducing the solar background radiation that reaches the photodetector.

Using the FADOF receiver, we have demonstrated that 27nW of received signal power gives a bit error rate of 10^{-6} (limited by the photoreceiver electronic noise) independent of solar noise up to 0.15Watt. We also repeated these measurements under the same operation conditions after replacing the FADOF with an interference filter. The experiments showed three orders higher background noise rejection capability for the FADOF receiver.

1. INTRODUCTION

Free space laser communication has evolved as an important possible alternative to microwave communications. But the rejection of the optical background radiation is still a serious problem. Any solar background radiation that reaches the photodetector will contribute to the photodetector shot noise current. This results in a reduced signal to noise ratio and hence an increased bit error rate. Thus the system performance in the presence of background radiation is an important characteristic of an optical communication system.

The Faraday Anomalous Dispersion Optical Filter (FADOF) provides a solution to this problem. FADOFs are narrow bandpass optical filters, which can provide a background noise rejection of $10^5 \sim 10^6$, while transmitting the signal with up to 80% efficiency. The FADOF signal bandwidth can be varied between 0.5 GHz and 5 GHz, a field-of view that is flat over $\pm 20^\circ$ and excellent imaging qualities. To illustrate its advantages, we have designed and built a laser communication system using the FADOF optical receiver and measured bit error rate versus the incident solar

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noise and the minimum signal power received by the photodetector needed to keep certain bit error rate, such as 10^{-6}. Next, we replaced the FADOF by a conventional interference filter and repeated the measurements under the same operating conditions. By comparing the results of these two cases, we demonstrated the FADOF system's ability to reject background radiation.

In our system, the signal wavelength is 780 nm and the data rate is 1 Mbit/sec. Figure 1. shows the system illustration. A mirror is installed on the roof of the O'Donnel Hall to reflect the signal light beam to the receiver and the location of the transmitter and receiver on the same place makes the system operation simpler and should pose no problems in data collection.

The transmitter and receiver are sufficiently separated so that the atmospheric scattering of the transmitted beam does not contribute significantly to the received signal.

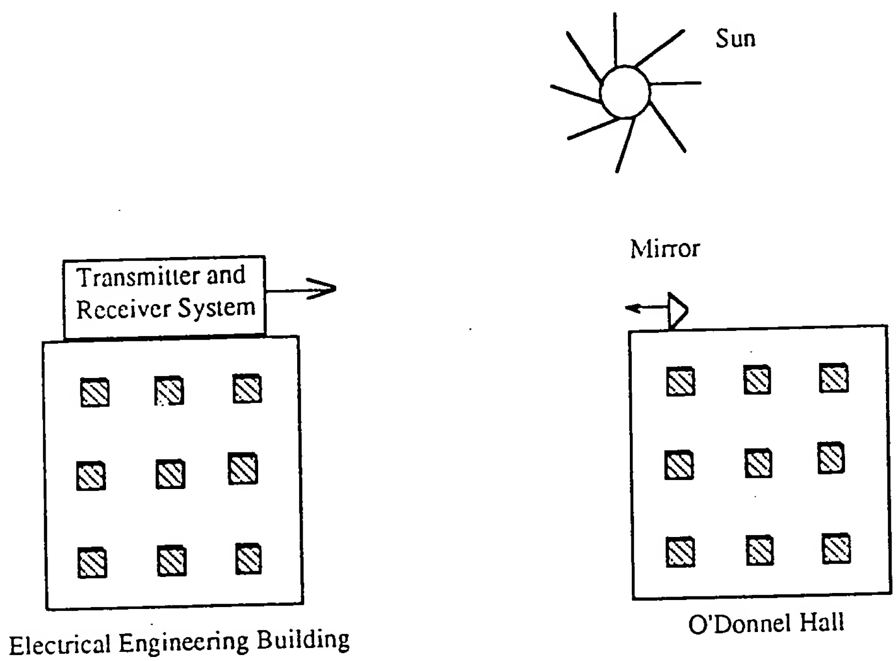

Figure 1. System Illustration

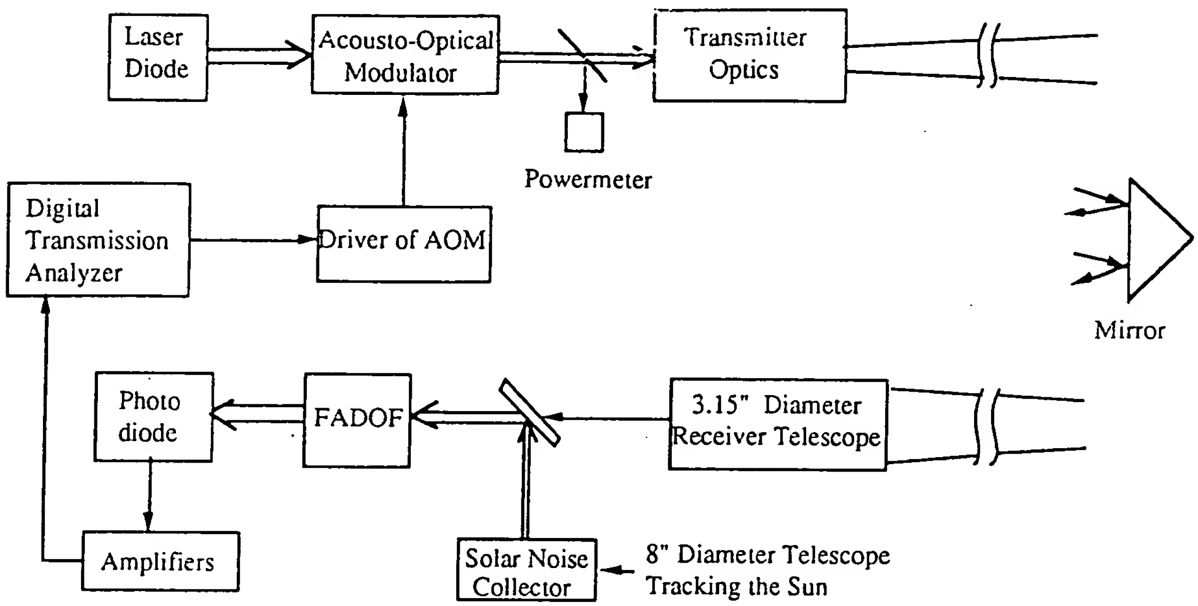

Figure 2. System Block Diagram

2. SYSTEM SETUP

A system block diagram is shown in Figure 2. For the experiment, the transmitter and receiver optical hardware are mounted on a covered optical testbed, so the system can be transported conveniently.

The light beam from the laser diode, after being collimated, is modulated by an Acousto-Optic Modulator. The modulator accepts a TTL drive signal. It has a rise time of 10 ns, an 1 mm aperture and an F number of 80. Using a power meter, we can tune the modulator to peak the modulation efficiency. The needed TTL signal is received from a Digital Transmission Analyzer (DTA) which is used to measure the bit error rate. Then the light beam passes through beam shaping optics and transmits to the receiver. In a practical free space laser communication system, the light beam is in the far field, that is, the transmission distance is much larger than the Rayleigh range of the gaussian beam. Therefore, we have designed the transmitter optics to ensure that the received beam is in the far field. After being reflected by the mirror mounted on the roof of the O'Donnel Hall, the laser beam is returned to the receiver telescope and passes through the optical filter. In a proposed deep space laser communication system, the receiver telescope diameter may be 10 meters[1]. The telescope can collect strong background radiation when it faces to the blue sky. In our demonstration system, the receiver telescope diameter is only several centimeters. To simulate the strong solar noise, we use an 8 inches diameter telescope tracking the sun as a solar radiation collector. Finally, the signal and background noise are mixed and focused onto the photodetector. The photodiode output is amplified to the TTL levels required by the digital transmission analyzer. In the DTA, the return information is compared with the DTA local signal

to obtain the bit error rate(BER). Without the solar background noise, by adjusting the transmitter laser power, we could maintain a given bit error rate as a constant, such as 10^{-6}, that is limited by the system sensitivity. After adding the solar noise, the bit error rate increases and the relationship between BER and SNR is obtained. Next, the FADOF is replaced by a conventional interference filter, which has a 10 nm bandwidth. Then we can compare the performance of the two receivers versus solar noise power.

3. THEORETICAL CALCULATION

3.1. Bit error rate analysis

In digital communications a common figure of merit is the bit error rate (BER). For a binary transmission system, assuming the binary levels (zero and ones) are equiprobable, the probability of error, P_e is

$$\mathrm{BER} = P_e = \frac{1}{2} P(1|0) + \frac{1}{2} P(0|1) \tag{1}$$

Where P(1|0) and P(0|1) represent the probability of false alarm and false dismissal respectively.
For on-off modulation, the bit error rate, BER, is[2]

$$\mathrm{BER} = 0.5*(1-\mathrm{erf}(0.5*\sqrt{\mathrm{SNR}_D})) \tag{2}$$

where the SNR_D is the signal to noise ratio for direct detection and the erf(x) is the error function,

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} * \int_0^x e^{-t^2} dt \tag{3}$$

Using Eq.2 we can easily calculate the bit error rate for a given signal to noise ratio. Therefore, in the next section we calculate the signal to noise ratio.

3.2. SNR calculation

For the direct detection receiver using a photodiode, the signal to noise ratio (SNR_D) is[3]

$$SNR_D = \frac{(R_i*P_{sig})^2}{2*e*B_e*R_i*(P_{sig}+\frac{P_{solar}}{NRF}) + R_i^2*NEP^2*B_e + \frac{4*k*T*B_e}{R_L*G^2}} \quad (4)$$

where:

R_i is the photodiode responsivity. P_{sig} is the signal power incident on the optical filter. B_e is the photodetector equivalent noise bandwidth. P_{solar} is the solar radiation power incident on the optical filter. NRF is the noise rejection factor of the optical filter. NEP is the noise equivalent power of the photodetector. G is the current gain of the photodetector. T is the temperature of the detector electronics. R_L is the load resistance of the postamplifier and k is the Boltzman's constant.

Clearly, increasing the noise rejection factor of the optical filter reduces the effect of the background noise. The noise rejection factor for the FADOF is about $10^5 \sim 10^6$, hence significant background noise suppression can be achieved.

4. EXPERIMENT RESULTS

The system operation conditions are

- . average signal power = 27nW
- . photodiode Noise Equivalent Power = $2.0*10^{-12}W/(Hz)^{1/2}$
- . data rate = 1Mbit/sec
- . electronic bandwidth = 4MHz

Without the background radiation, to keep BER = 10^{-6}, the system sensitivity, 27nW, is limited by the photodiode electronic noise. Table 1. shows the measured bit error rate versus the solar noise incident on the optical filter for two different receiver systems using FADOF and interference filter in the receiver. Figure 3. plots bit error rate versus signal to noise ratio. The continuous line is the theoretical curve and the bars and the arrow are the measured points for the interference filter and the FADOF receiver respectively.

P_{solar}(W) incident on filter	Measured Bit Error Rate		SNR	
	FADOF	IF	FADOF	IF
0.0	$0\sim1*10^{-6}$	$0\sim1*10^{-6}$	43.0	43.0
$1.13*10^{-4}$	10^{-6}	$3\sim4*10^{-5}$	--	34.7
$3.75*10^{-4}$	10^{-6}	$5*10^{-4}$	--	27.8
$1.25*10^{-3}$	10^{-6}	$2.0*10^{-3}\sim8.0*10^{-2}$	--	16.7
$9*10^{-3}$	10^{-6}	10^{-1}	--	3.7
0.15	10^{-6}	10^{-1}	--	0.24
2.5*	10^{-6}		37.5	

* the maximum theoretical incident solar noise power to keep BER=10^{-6}

Table 1. BER and SNR vs. Solar Noise Power

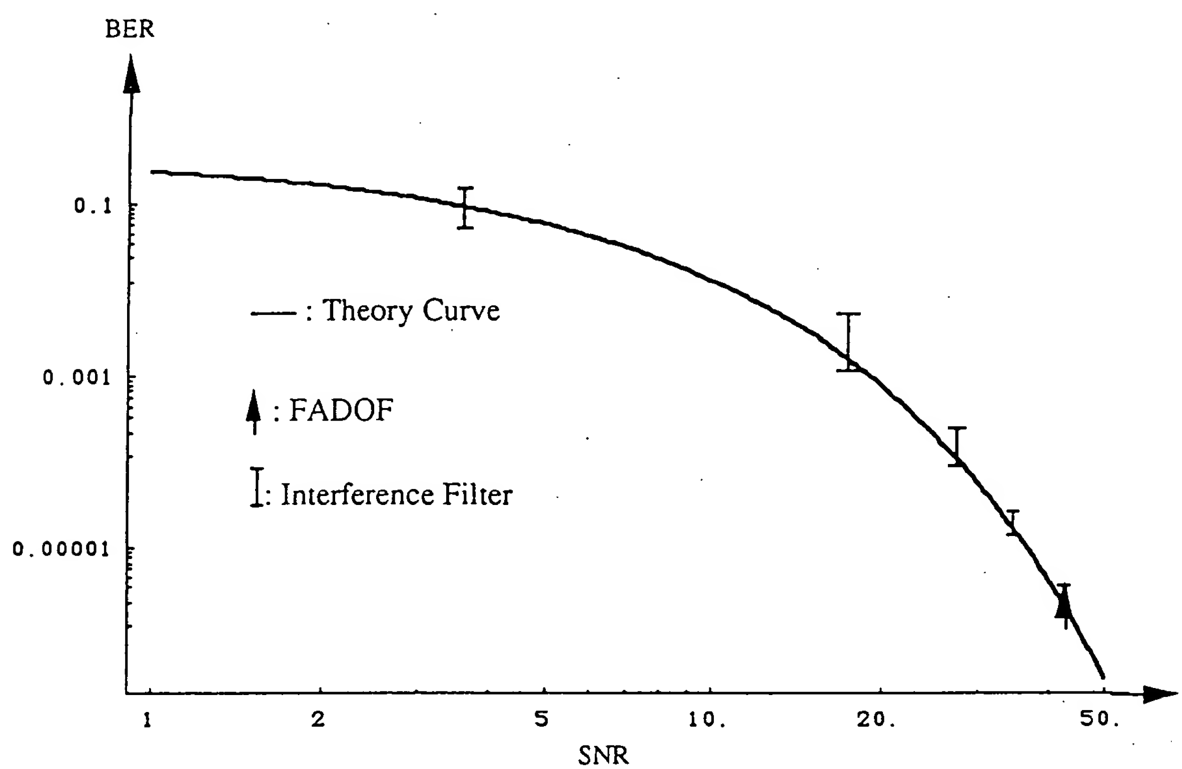

Figure 3.. Bit Error Rate vs. Signal to Noise Ratio

The experimental results have shown that the FADOFs have at least three orders higher background noise rejection capability than that of the interference filters when the incident solar noise power increased from 0.0W to the maximum available value, 0.15W, which is limited by the active area of the photodiode. The remarkable thing is that, for the FADOF, the bit error rate maintained on the value of 10^{-6}. Thus, on the BER vs. SNR graph, it appeared only as one point shown by an arrow.

For the interference performance, the error between the theory and the experiment is mainly induced by mechanical stability problems. T he main problem is the mechanical stability of the solar radiation collection telescope.

For the sensitivity measurement without the solar noise, the measurement error was less than 5%. When the incident solar radiation is big enough, the signal was submerged by the noise, so the bit error rate approached the maximum value, 10^{-1} limited by the digital transmission analyzer.

5. SUMMARY AND OUTLOOK

We have built a laser communication system that uses either a FADOF or a conventional interference filter in the receiver. We measured the system performance for both systems. The experiments showed three orders higher background noise rejection capability for the FADOF receiver. The maximum incident solar radiation of the photodiode is limited by its active area. The system sensitivity is limited by the PIN photodiode electronic noise. We will use a 16mm active region diameter APD detector to show even higher background noise rejection capability of the FADOF receiver and improve the system sensitivity. We will report the results in future

6. ACKNOWLEDGMENTS

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